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DYNAMIC CHARACTERIZATION OF INTERCRITICALLY ROLLED HIGH-HARDNESS STEEL

MORRIS AZRIN, ALBERT A. ANCTIL, and ERIC B. KULA

METALS RESEARCH DIVISION

June 1982

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ABSTRACT

Two compositions of intercritically rolled homogeneous steel armor were evaluated by quasi-static and dynamic tests. Cross-rolling just below the intercritical temperature resulted in improved fracture toughness at the high-hardness levels (55 and 58 HRC). Taylor cylinder ballistic impact tests indicated a dynamic stress more than double the quasi-static yield stress. The use of this test for evaluating potential high-hardness armor material is discussed.

INTRODUCTION

Higher hardness in armor plate generally leads to improved ballistic performance.[1] The limiting factor at high-hardness levels is gross plate shattering, which rapidly reduces the ballistic limit. This limitation has led to the use of dual-hard armor with a high-hardness front plate and relatively ductile metallurgically roll-bonded rear plate. The high processing costs of dual-hard armor, however, have led to their replacement by specially processed rolled homogeneous steel armor.

Recently, a comprehensive study was undertaken by the U.S. Steel Corp. to develop steel compositions and processing techniques to attain high-hardness armor with adequate shatter resistance.[2,3] For the quench-and-tempered steels it became apparent that the optimum rolling temperature was slightly below the ferrite-austenite A_3 transformation temperature. The interest in intercritical* (IC) rolling was based on earlier work on IC heat treatments that produced increased strength and fracture toughness,[4-8] along with reduced back spalling during ballistic impact.[2] The resultant microstructure of reduced banding, microstructural refinement, and finely dispersed α(ferrite) and α' (martensite) regions is desirable in terms of ballistic performance.

A natural extension of IC heat treatments is the use of IC rolling to further refine the microstructure. This is possible since the low temperatures used essentially prevent recrystallization. The two hypoeutectoid steels (Table 1) that are the subject of this study were obtained from the U.S. Steel Corp. The transformation and processing temperatures are shown in Table 2. A number of microstructural features are a direct result of IC rolling. Intercritical holding time is also a factor since a high-carbon austenite results from the α-phase rejection of carbon. The finely dispersed α-regions are refined during IC rolling, producing a layered microstructure of ferrite and austenite. On quenching, after IC rolling, α' forms in the austenite and the resulting retained austenite and banded $\alpha+\alpha'$ would be expected to provide improved longitudinal fracture toughness. This microstructure can be undesirable, however, in armor applications where failure by delamination is strongly influenced by microstructural layering. On the other hand, refining the microstructure by thermomechanical treatments should result in spalling resistance at least equivalent to that of conventionally processed rolled homogeneous armor. Crystallographic preferred orientations produced in the austenite at high temperatures are not destroyed on quenching. The high carbon γ (austenite) transforms to high carbon α'.

*The intercritical region is the two-phase α-γ region bounded by A_1 and A_3.

1. MANGANELLO, S. J., and ABBOTT, K. H. *Metallurgical Factors Affecting the Ballistic Behavior of Steel Targets.* J. of Materials, v. 7, no. 2, June 1972, p. 231-239.
2. CARSON, C. G., DABKOWSKI, D. S., SPAEDER, G. J., and PORTER, L. F. *A Research Study on the Relative Merits of Homogeneous and Dual-Hardness Armor Produced by Special Processes (U).* U.S. Steel Corp., Contract DAAG46-71-C-0136, Final Report, AMMRC CTR 72-14, September 1972, AD 522367 (Confidential Report).
3. SPEICH, G. R., HU, H., and MILLER, R. L. *Effect of Preferred Orientation and Related Metallurgical Parameters on Mechanical Properties and Ballistic Performance of High-Hardness Steel Armor.* U.S. Steel Corp., Contract DAAG46-73-C-0244, Final Report, AMMRC CTR 74-39, June 1974.
4. DULIEU, D., LATHAM, D. L., BANNISTER, J. W., and GIBSON, S. *Controlled Rolling of Carbon and Low Alloy Steel.* BISRA Open Report, MG/INT/73/70, British Steel Corp., 1970.
5. GRANGE, R. A. *Fibrous Microstructures Developed in Steel by Thermomechanical Processing.* Proc. Second International Conference on the Strength of Metals and Alloys, ASM, Menlo Park, Ohio, 1970, p. 861-876.
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7. MARCHENKO, V. G. *Quenching of Steels from Intercritical Temperatures.* Metal Science and Heat Treatment, v. 17, March-April 1975, p. 245-246.
8. WADA, T., and DOANE, D. V. *The Effect of an Intercritical Heat Treatment on Temper Embrittlement of a Ni-Cr-Mo-V Rotor Steel.* Met. Trans., v. 5, 1974, p. 231-239.

Quenching from below A_3 reduces the amount of retained γ. These factors are known to influence strength, toughness, and the resultant penetration resistance.[1-3] Carson et al.[2] found that quench-and-tempered IC rolled homogeneous armor plate had improved ballistic performance without plate shattering.

Table 1. CHEMICAL COMPOSITION, WEIGHT PERCENT*

Material	Mn	P	S	Si	Ni	Cr	Mo	Al	N	V	Cu
0.39C	0.60	0.005	0.007	1.29	5.46	--	0.49	0.031	0.009	0.10	0.94
0.47C	0.66	0.006	0.007	0.32	1.10	0.76	0.51	0.024	0.008	0.26	--

*Material obtained from U.S. Steel Corp. in the processed condition.

Table 2. TRANSFORMATION AND PROCESSING TEMPERATURES*

Material	Austenitizing Temp. (°F)	Transformation Temp.* (°F)		Rolling Temp. (°F)	HRC
		A_1	A_3		
0.39C	2200	1225	1440	1365	56
0.47C	1800	1325	1495	1420	58

*Calculated values (Ref. 2).

The two compositions in Table 1 were studied to determine the dynamic characteristics important to armor applications. In addition to tensile and fracture toughness testing, Taylor projectile impact tests were also conducted.[9,10] Material characterization requires that test conditions be relevant to those encountered in service. This is particularly true for armor applications where strain rates above 10^4 sec^{-1} are encountered. The Taylor impact test relates the length change of an impacted flat-end projectile to a dynamic flow stress. The test procedure is relatively simple. The projectile is fired at a right angle to a rigid, thick target. Low impact velocities are used to prevent fracture. Contrary to expectations, the measured Taylor stress of moderate strength materials is nearly independent of projectile impact velocity.[10-13] These expectations are based on tension and compression results in the 10^{-4} to 10^3 sec^{-1} strain rate range. However, a collection of tension and compression results by Soohoo et al.[14] show the strain rate dependence of yield strength, though significant at low- and intermediate-strength levels, becomes negligible at the high strength levels.

Measurement of the impact velocity and deformed projectile length permit calculation of the Taylor dynamic flow stress Y^o from the equation:

9. TAYLOR, G. I. *The Use of Flat-Ended Projectiles for Determining Dynamic Yield Stress. I: Theoretical Considerations.* Proc. Royal Soc., v. A 194, 1948, p. 289-299.
10. WILKINS, M. L., and GUINAN, M. W. *Impact of Cylinders on a Rigid Boundary.* J. Appl. Phys., v. 44, no. 3, 1973, p. 1200-1206.
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13. KARNES, C. W., and BERTHOLF, L. D. *Inelastic Behavior of Solids.* McGraw-Hill, New York, 1970.
14. SOOHOO, P., JIANG, C. W., and CHEN, M. M. *Dynamic Properties of Materials, Part III - Steels.* Boston University, Contract DAAG46-73-C-0181, Final Report, AMMRC CTR 74-24, April 1974.

$$\frac{L_f}{L_o} = \exp\left[-\frac{\rho V^2}{2Y^o}\right], \tag{1}$$

L_f = final projectile length,

L_o = original projectile length,

ρ = density, and

V = impact velocity.

In Equation 1 Y^o represents an "average" flow stress that a cylindrical rod experiences as it decelerates and deforms into a mushroom-shaped rod. The length measurement is made after the impacted end of the projectile undergoes gross deformation with negligible, if any, deformation at the opposite end of the projectile. Therefore, Y^o represents neither a yield stress nor ultimate stress (i.e., stress at maximum load).

Tests by Taylor[9] and others,[10-13,15] were performed using low strength materials. In all cases, Y^o was higher than the quasistatic value. More recently, Papirno et al.[16] applied the Taylor test to high-strength 4340 steel and found that the dynamic stress was almost double the static compression yield stress.

MATERIALS

The rolled homogeneous armor steels tested (Table 1) were received in the IC rolled-and-tempered condition. The higher carbon alloy is a standard armor steel (0.50C-1.1Ni-0.75Cr-0.50Mo) modified with 0.2 percent vanadium. Although the alloys were intercritically cross-rolled with a final rolling ratio of one-to-one, there was still microstructural evidence of a "rolling direction." All mechanical test specimens were oriented with reference to the apparent longitudinal direction of the 5/8-inch-thick plates.

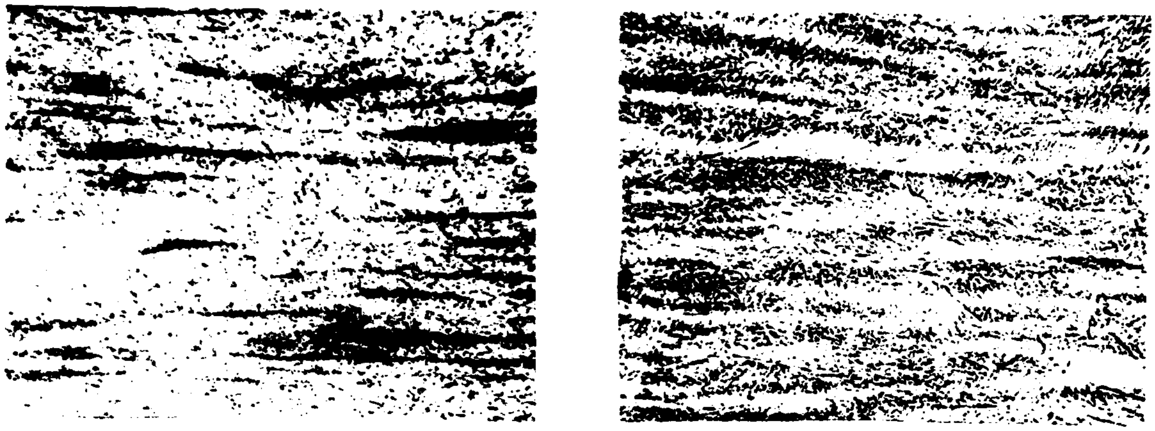
Figure 1 shows the heavily banded structure for both alloys. Areas (dark) of dense carbide precipitation are also evident. At higher magnification, the 0.47C alloy has a finer lath martensite packet size. Rolling conditions and quench rates produced no noticeable difference in microstructure at the surface and midsection planes (Figure 2). The 0.47C alloy has a finer grain structure with carbides strung out along prior austenite grain boundaries. The bands appear as patches when viewed normal to the plate (Figure 2).

EXPERIMENTAL PROCEDURES

Selected room temperature tests were performed to complement those reported by the U.S. Steel Corp. Research Laboratory.[2,3] Static tension tests were performed parallel to the plate rolling direction. Computerized instrumented Charpy testing equipment was used to obtain the dynamic fracture toughness data. Charpy impact and dynamic fracture toughness tests were performed in the LT and TL directions.

15. POLOSATKIN, G. D., KUDRYAVTSEVA, L. A. and GLAZKOV, V. M. *Russian Metallurgy*, no. 5, 1966, p. 62-64.
16. PAPIRNO, R. P., MESCALL, J. F., and HANSEN, A. M. *Proceedings of the Army Symposium on Solid Mechanics, 1980 - Designing for Extremes: Environment, Loading, and Structural Behavior.* Army Materials and Mechanics Research Center, AMMRC MS 80-4, September 1980, p. 367-385.

Taylor impact projectiles, 0.218-inch diameter and 0.436-inch long, were machined from a 5/8-inch plate with the specimen axis in the short transverse and longitudinal directions. The projectiles were fired from a 0.218-inch-diameter smooth bore light gas gun at a thick hardened-steel plate. Precautions were taken to ensure normal impact and accurate final length (L_f) measurements.* Velocities were measured with a pair of silver-coated paper screens located close to the target.



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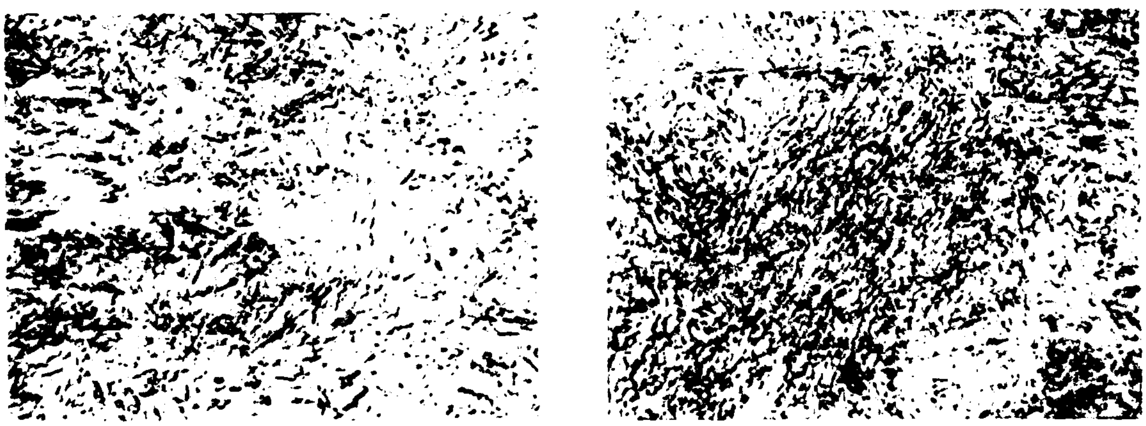

(a)

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Figure 1. Photomicrographs of the plane normal to the rolling direction (a) for the 0.47C and (b) for the 0.39C homogeneous intercritically rolled steel armor. Picral etch.

*PAPIRNO, et al.[16] clearly demonstrated that for high-strength materials, where length shortening is small, the uncertainty in L_f can result in a significant error in the calculated Taylor stress.

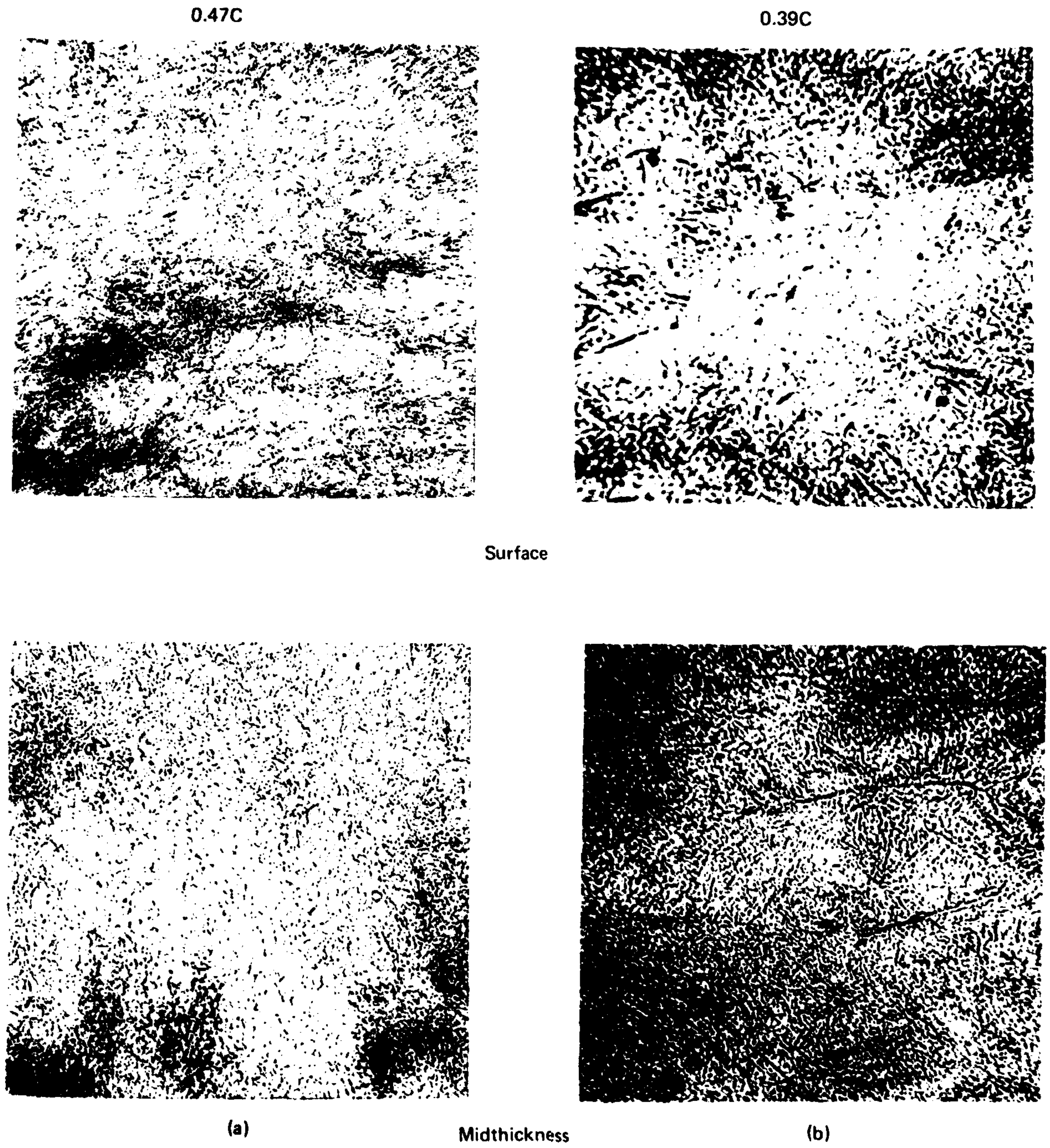

Figure 2. Photomicrographs of the plane parallel to the rolling direction (a) outer surface plane (b) plane at midthickness of homogeneous intercritically rolled homogeneous armor. Picral etch. Mag. 100X.

RESULTS AND DISCUSSION

The 0.47C steel, as expected, had higher hardness and static strength levels (Tables 2 and 3), lower ductility (Table 3), and lower Charpy impact energy (Table 4). The lack of orientation effects for both steels are a result of cross-rolling. The Charpy energy levels are slightly higher than other high strength steels.[17] Apparently, at these moderate strain rates, IC rolling and the structural refinement are beneficial. Similar results are found for the dynamic fracture toughness specimens (Table 5). Again, fracture toughness is lower at the higher strength level, orientation plays no significant role, and values reported are higher than for comparable high strength steels.[18]

Table 3. LONGITUDINAL TENSILE PROPERTIES

Material	0.2% YS (ksi)	UTS (ksi)	TFS (ksi)	n	Elon. (%)	RA (%)
0.39C	226	320	409	-	11	29
	226	317	392	0.09	9	25
	240	317	401	0.09	11	29
0.47C	266	351	411	-	7	20
	275	353	415	0.08	9	20
	-	355	420	0.07	7	21

TFS - True Fracture Stress

n - Strain Hardening Exponent

Table 4. CHARPY IMPACT ENERGY

Material	Orientation	Energy ft-lb
0.39C	LT	19.4
	LT	15.2
	TL	15.5
	TL	17.8
0.47C	LT	10.3
	LT	12.1
	TL	11.2
	TL	11.2

Table 5. DYNAMIC FRACTURE TOUGHNESS

Material	Orientation	K_{ID} (ksi$\sqrt{\text{in.}}$)
0.39C	LT	62.3
	TL	73.2
0.47C	LT	53.1
	TL	52.6

17. TUFFNELL, G. W., and CAIRNS, R. L. *18% Nickel 350-Maraging Steel.* Trans. ASM, v. 61, 1968, p. 798-806.
18. WOOD, W. E., PARKER, E. R., and ZACKAY, V. F. *An Investigation of Metallurgical Factors Which Affect Fracture Toughness of Ultra-High Strength Steels.* University of California, Contract DAAG46-72-C-0220, Final Report, AMMRC CTR 73-24, May 1973.

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Table 6 lists the cylinder impact test results along with specimen orientations. There is a lower and upper velocity limit that can be used for these tests. The higher velocities produced excessive deformation resulting in specimen fracture along a 45° shear plane (Figure 3). This observation is consistent with the reported cone-shaped fracture observed in cylinder impact tests of high strength 4340 steel.[16] At lower velocities (not shown in Table 6) length shortening was insignificant. The impact data suitable for Taylor model calculations are shown with an asterisk. The harder, higher carbon alloy has the higher dynamic Taylor stress Y^o while both steels show no strong orientation effect. The Y^o is more than double the static 0.2 percent yield stress.

Table 6. CYLINDRICAL IMPACT DATA

Material	Orientation	Velocity (ft/sec)	Original Length L_o (in.)	Final Length L_f (in.)	L_f/L_o	Y^o (ksi)	Impact Observation
0.39C	Short Transverse	640	0.440	0.424	0.963		Shear Cracking - No separation
		697*	0.441	0.422	0.956	578	Deformation - No cracking
		706	0.441	-	-		Shear Fracture
		730	0.439	-	-		Shear Fracture
		735	0.441	0.418	0.947		Shear Cracking - No separation
		776	0.442	-	-		Shear Fracture
		820	0.440	-	-		Shear Fracture
	Longitudinal	630	0.440	-	-		Shear Fracture
		635	0.440	0.425	0.966		Shear Cracking - No separation
		653	0.441	-	-		Shear Fracture
		654	0.441	0.423	0.959		Shear Cracking - No separation
		657	0.441	-	-		Shear Fracture
		658	0.442	-	-		Shear Fracture
		658*	0.442	0.425	0.962	578	Deformation - No cracking
		672	0.441	-	-		Shear Fracture
0.47C	Short Transverse	637	0.441	0.427	0.968		Shear Cracking - No separation
		639	0.440	-	-		Shear Fracture
		643*	0.441	0.428	0.969	724	Deformation - No cracking
		648	0.439	-	-		Shear Fracture
		648	0.441	-	-		Shear Fracture
		649	0.440	-	-		Shear Fracture
		651	0.442	-	-		Shear Fracture
		668*	0.440	0.426	0.968	722	Deformation - No cracking
	Longitudinal	607*	0.440	0.427	0.969	643	Deformation - No cracking
		607	0.441	0.429	0.973		Deformation - Crack initiation
		609	0.441	-	-		Shear Fracture
		611	0.441	0.430	0.974		Deformation - Crack initiation
		616	0.439	-	-		Shear Fracture
		645*	0.441	0.428	0.970	728	Deformation - No cracking
		650	0.438	0.424	0.968		Shear Cracking - No separation
		650	0.440	-	-		Shear Fracture

*Data used in Taylor Calculation

The quasi-static yield, Charpy impact, and Taylor impact results are summarized in Figure 4 and compared with published data for quenched-and-tempered AISI 4340 steel.[16,19-25] The Y^o band[16] represents two L/D ratios, the L/D = 2 ratio generally having higher values than L/D = 4. The most significant observation is the high value of Y^o for the IC rolled material. At the high-hardness level Y^o for the 4340 steel is double the quasi-static tensile yield strength. This ratio is approximately 2-1/2 for the IC rolled material. The reason for the superior performance of the intercritically rolled material is not known.

The experimental simplicity and ease of calculations make the Taylor test desirable for evaluating potential armor materials. A high dynamic Taylor stress (actually an approximate average flow stress) would give some guidance in the search for increasing hardness and impact resistance. Unfortunately, no studies have been reported relating armor performance and the calculated Y^o. In addition, there is only a small body of literature comparing quasi-static and Taylor impact tests for low-strength materials. Only recently have results been reported for high-strength alloys.[16] Based on experimental and theoretical analysis, Papirno et al.[16] concluded that Equation 1 is nonconservative when applied to high strength steels. Also included in that paper is a discussion of the experimental sophistication necessary for the Taylor test.

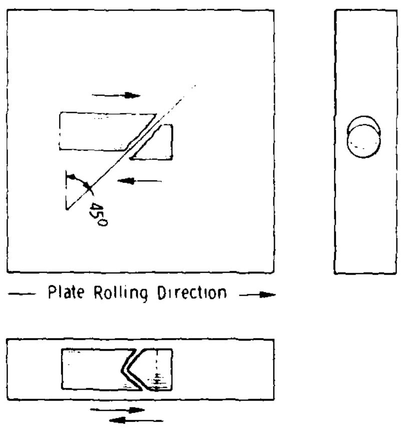

Figure 3. Cylindrical fracture plane.

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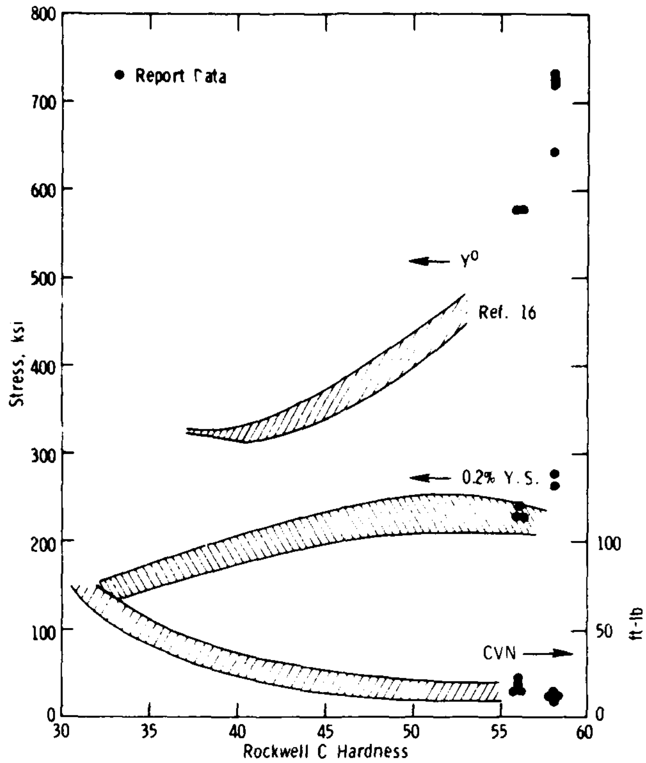

Figure 4. Taylor stress, tensile yield stress, and Charpy impact energy of quenched-and-tempered AISI 4340 steel (shaded areas, Ref. 16, 19-25) and intercritically rolled steel.

CONCLUSIONS

1. Intercritically rolled homogeneous armor steel has higher strength and toughness than armor processed by a conventional quench-and-temper treatment.

2. The dynamic Taylor flow stress Y^o, obtained from the cylinder impact test, is more than double the quasi-static tensile yield strength of the two steels tested.

3. The relatively simple Taylor impact test is a potential method of evaluating candidate armor materials.

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